Finding and Using Electromagnetic Counterparts of Gravitational Wave Sources

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Abstract

The principal goal of this whitepaper is not so much to demonstrate that gravitational wave detectors like LIGO and LISA will help answer many central questions in astronomy and astrophysics, but to make the case that they can help answer **a far greater range of questions** *if we prepare to make the (sometimes substantial) effort to identify electromagnetic counterparts to the gravitational wave sources.*

1 Extreme Sports in the Universe: past decades

The most dramatic events in the universe —the deaths of stars, the collisions of stellar remnants and giant black holes, the feeding of the monsters in galactic nuclei —are believed to produce the most electromagnetically luminous objects in the universe: supernovae, gamma-ray bursts, quasars.

The objects involved in these events are worthy of study for three reasons: 1) their intrinsic interest and the great distances to which they can be seen, 2) the impact of the energy they release on the rest of the astronomical universe, and 3) (perhaps most significantly) because they test our theories of matter and energy in ways we cannot hope to do on earth. They involve the most extreme physical conditions in the present universe: the highest densities of both matter and radiation, the highest magnetic fields, the deepest gravitational fields, the most relativistic bulk motions.

In previous decades, we have studied these events using just the light emitted from them (plus a couple of dozen marvelous neutrinos from supernova 1987A). This light comes from atoms and electrons in tenuous gas, generally far removed from the main action. Because this action is buried deep behind layers of obscuring gas and in deep gravitational potential wells, the light we can see has given us many circumstantial clues, but the deepest questions remain unanswered.

- How and why do some stars explode as supernovae?
- Are the things we call black holes actually precisely the vacuum space-time solutions of the equations of general relativity?
- How and when do black holes form in stars and in the centers of galaxies?
- Do black holes form in other places?
- How do gas, stars and black holes interact in the nuclei of galaxies and compact clusters?
- What are the internal ingredients of neutron stars?
- What happens when two white dwarfs merge?

2 The next decade: adding information from gravitational waves

Strong gravitational waves are produced by the rapid motion of massive compact bodies: exactly those extreme objects discussed above. The waves encode the history of those motions: exactly the information that has proven so difficult to obtain electromagnetically. Gravitational waves will provide us with a detailed look deep into the interiors of the most exotic objects in our Universe. Ground-based detectors such as enhanced-LIGO (2009) and

advanced LIGO (2014) will detect high-frequency (**HF**) gravitational waves ($\sim 10-1000$Hz) [1]. They can detect the merging of binary black holes, and the tidal disruption and merger of neutron stars in black hole and neutron star binaries at ∼50Mpc and ∼200Mpc respectively. They may also be able to detect accretion-induced collapse events, and some types of supernovae and pulsars [2]. The ESA-NASA space-based mission LISA will detect low-frequency (**LF**) gravitational waves (0.1-10mHz) [3, 4]. It can detect merging binary supermassive black holes (to $z \sim 30$), their captures of intermediate mass black holes (to $z \sim 3$), and their captures of the compact objects (stellar mass black holes to $z \sim 1$, neutron stars and white dwarfs to $z \sim 0.1$) in galactic nuclei. It will measure the masses, spins and distances of all these objects to precisions unprecedented in astrophysics. It will also measure the orbital parameters of thousands of ultracompact binary stars in the Milky Way and its satellites.

From the gravitational waveforms we will be able to decode precise information about the masses, spins, distances, interior properties and space-time dynamics of the detected sources. This information will be of an accuracy and robustness far exceeding what can be obtained by electromagnetic measurements. Alone, these will enable precision tests of general relativity in the strong-field limit[5, 6] and the structure and dynamics of compact objects, and tell us about the merger rates as a function of cosmic time for supermassive black holes[7], intermediate mass black holes, and stellar mass black holes, neutron stars and white dwarf binaries of all types[8, 9].

3 Why electromagnetic counterparts to gravitational wave sources are so important

However this new information from gravitational waves can have a far broader impact if it can be put into the context of our existing electromagnetic view of the universe.

Imagine the frustration of measuring gravitational waves from what appears to be the formation of a rapidly spinning neutron star, but missing the electromagnetic counterpart that would determine that it was from a massive type Ic supernova in a starburst galaxy, not an accretion-induced collapse of an accreting white dwarf in the outskirts of an elliptical galaxy.

And what a lost opportunity if gravitational waves measured the properties of a merging pair of massive black holes, but we missed the electromagnetic fireworks that would have enabled us to identify the host high-redshift galaxy and its clustering environment, and to diagnose the properties of the black holes' circumbinary gas disk.

Gravitational waves alone will generally determine sky positions only to ∼ degrees [1]. In a few cases, bright electromagnetic events such as nearby gamma-ray bursts or supernovae may trigger LIGO searches[10]. But most commonly, gravitational wave detections by LIGO and LISA will have to trigger electromagnetic searches, because many of the predicted coun-

[1] Tens of degrees for short-lived LF (LISA) sources and high-frequency sources (LIGO), improving for sources with > year lifetimes to ∼ 0.1 degree for strong LISA sources and arcseconds for strong LIGO sources.

terparts are faint (V magnitudes 18-27) and can be short-lived and inconspicuous. Much effort on the part of electromagnetic observations will be required to identify them in the error boxes that may be as large as tens of square degrees. Wide field synoptic survey instruments with a fast cadence are ideal (e.g. Palomar Transient Factory, Pan-Starrs, SkyMapper, LSST in the optical, plus wide-field or all-sky radio, X-ray and gamma-ray instruments[11]). Finding electromagnetic counterparts will require rapid, but feasible data analysis and dissemination from the gravitational wave detectors (within minutes to hours for short-lived HF sources, and days to weeks for merging LF sources).

Fortunately, finding counterparts of both HF and LF gravitational wave sources requires quite similar electromagnetic instrumentation, of a type envisaged for the coming decade. Flexibility in the cadences and modes of operation will, however, be required.

In the subsections below, we give just a few selected examples of science questions that could be answered by combining electromagnetic and gravitational wave data on the sources listed. The tables briefly summarise additional topics for which space precludes discussion. [2].

3.1 What causes some pairs of dead stars to merge, and others not to?

The fates of interacting binary stars remain poorly understood, despite their importance for the nature, formation and evolution of Type I (a,b,c) supernovae, binary pulsars, X-ray binaries and cosmic nucleosynthesis. A priori calculations involve accretion disks, magnetic fields, and the 3-D radiation hydrodynamics of common-envelope evolution. Parametrised population synthesis has many uncertainties and difficulties explaining existing population data, which is however subject to severe selection effects.

LISA will provide a complete Galactic sample orders of magnitude larger than the handful of ultracompact binaries now known, measuring the individual parameters of about 20,000 ultracompact white dwarf binaries (orbital periods less than around 30 minutes) in the Milky Way and its satellites [12], along with a less well-determined number of neutron star and black hole binaries. The frequency f of the gravitational wave signal is twice the orbital frequency. The polarisation of the gravitational wave signal determines the orbit inclination and orientation on the sky. The amplitude of the gravitational signal $h \propto f^{2/3}\mathcal{M}^{5/3}/D$ depends on the chirp mass $\mathcal{M} = (M_1 M_2)^{3/5}(M_1 + M_2)^{-1/5}$ and distance D to the source. If the components are not interacting by mass transfer or tides, the orbital frequency evolution $\dot{f}$ is determined just by gravitational radiation (and the braking index $\ddot{f}f/\dot{f}^2 = 11/3$), and D can be determined accurately for the ~ 3000 ultracompact binaries for which $\dot{f}$ will be measurable. But for many of the white dwarf binaries, tides and mass transfer will affect $\dot{f}$, even in sign. For these, $\mathcal{M}$ can still be determined from h if D is known. GAIA will measure parallaxes for at least ~ 400 (more if tidal heating is important) eclipsing binary

[2]In keeping with US legal tradition "innocent until proven guilty", we use the term "dead stars" instead of the more common terms "compact objects" or "white dwarfs, neutron stars, and black holes", which presuppose proof beyond a reasonable doubt.

white dwarfs, with substantial overlap with the LISA sample, so for these sources, the combination of EM and GW information will determine the component radii, masses and orbital dynamics[13]. Identifying these eclipsing white dwarf pairs in the $\sim 1^\circ$ error boxes from LISA will require fast (minute cadence) wide field synoptic surveys to $V = 19$, and followup with high-speed spectroscopy of the identified sources.

Source	GW data	GW+EM data
ultracompact binaries (LISA)	complete census in Milky Way and satellites, binary periods, component masses, orbit inclination and orientation, in- or out-spiral rates, formation rate, merger rate	parallaxes (GAIA) needed for some GW masses, eclipses: white dwarf radii, white dwarf temperatures: tidal heating?, tidal synchronisation?, accretion rates and types (disk, direct impact, magnetic guiding), winds, SN Ia, AIC?

3.2 What happens during the mergers of dead stars, and what determines the nature of their remnants?

Merging neutron star binaries (and/or neutron stars tidally disrupted in merging neutron star-black hole binaries) have been proposed as the engines of short-hard gamma-ray bursts, r-process nucleosynthesis, and ultra-high energy neutrinos. Yet these identifications remain hypothetical for lack of evidence. Gravitational wave detections will settle the matter. But because of relativistic beaming, the majority of mergers may not be detectable as gamma-ray bursts, and such optical and radio afterglows (likely less beamed) as have been seen are faint, and will require concerted effort from wide-field synoptic survey telescope and much followup to distinguish them from other transient sources. Yet the payoff will be tremendous —for example, the gravitational waveform will determine the orbit inclination as well as component masses and radii and the time of merger. This will provide vastly improved constraints on models of the electromagnetic emission as a function of angle from the angular momentum axis.

Similarly, a combination of gravitational wave and electromagnetic detections could immediately clarify our uncertainty about what happens when two white dwarfs or a white dwarf and a neutron star accrete and merge: outcomes range from neutron stars or black holes (accretion-induced collapse, AIC) to various explosive ejections up to type Ia supernovae.

Source	GW data	GW+EM data
NS-BH (LIGO)	masses, spins, NS radius/structural parameters, orbit inclination and orientation	Gamma-rays (GRB?), jet and outflow (afterglow) properties as function of GW-determined inclination, neutrinos, nucleosynthesis.
NS-NS (LIGO)	masses, neutron star radii/structural parameters	Gamma-rays (GRB?), jet and outflow (afterglow) properties as function of GW-determined inclination, neutrinos, nucleosynthesis.
WD-WD, WD-NS (LIGO, LISA)	final NS or BH mass, radius, spin	nucleosynthesis, outflow energetics, explosion vs remnant?, magnetic field of AIC remnant

3.3 What are the fates of stars and stellar remnants near the giant black holes in galactic nuclei?

Observations of the center of our Milky Way and other nearby galaxies have revealed that short-lived massive stars form surprisingly close to the supermassive black holes that lurk there. Mass segregation implies that black hole remnants of such stars should be the dominant population close to the black hole, and they would provide valuable clues to the star formation history and stellar dynamics in galactic nuclei. Detection of these is only possible through gravitational radiation. White dwarfs may be tidally disrupted late in their inspiral, providing both electromagnetic and gravitational wave signatures and the combination of gravitational wave determined distance (see section 3.1) and electromagnetic redshift would enable precision cosmography [14, 15]. These sources also will provide maps of the spacetime geometry of unprecedented precision (black hole multipole moments with precision as high as $\sim 10^{-4}$). While these enable tests of strong-field general relativity ([5]), comparison of the unambiguously known masses and spins for a population of quiescent and active black holes will at last provide a firm basis for electromagnetic models of accretion and the evolution of black holes in galactic nuclei ([8, 7]).

Source	GW data	GW+EM data
extreme mass ratio inspiral onto massive black holes in galactic nuclei (LISA)	mass, spin of massive black hole, mass of compact object, distance, high-precision spacetime, merger rate and dead star mass function in local universe, orbit eccentricity, inclination, orientation	redshift, host galaxy ID, properties and dynamics of host nucleus, GW advance notice for EM study of tidal disruption of white dwarfs, brown dwarfs of known M,R.

3.4 How and when do black holes form in the centers of galaxies?

The field of electromagnetic counterparts of merging supermassive black holes has burgeoned in the past few years [16, 15]. Signatures range from prompt optical, UV and X-ray flares to year-timescale events in infrared and other bands. Identification of these transients will enable us to identify the host galaxy, testing models of galaxy mergers, and also, because of the known time and amplitude of disk perturbation around a black hole of known mass, potentially revolutionise the study of accretion disks, as well as testing modified gravity models by comparing the electromagnetic and gravitational $z - D_L(z)$ relations [15].

Source	GW data	GW+EM data
merging massive or intermediate mass black holes (LISA)	masses, spins (initial and final), distances, merger rates, spacetime dynamics	host galaxy morphology, luminosity, dynamics, redshift; circumbinary gas disk properties and response to mass loss, kicks, gravitational waves; magnetodynamics

3.5 How and why do some stars explode as supernovae?

Most supernovae probably are not strong sources of gravitational waves, but the most interesting ones (e.g. rapidly rotating hypernovae implicated in long-duration gamma-ray bursts, magnetar progenitors, etc) may be [17]. These gravitational waveforms will likely only be identified in coincidence with electromagnetic observations, but would provide a view of the interior dynamics of supernova unobtainable in any other way.

Source	GW data	GW+EM data
Supernovae (LIGO)	extreme core (magneto) hydrodynamics and instabilities, rotation, bars	relation of core dynamics to explosion type, progenitors, nucleosynthesis, black hole vs neutron star remnant

3.6 What are the internal ingredients of neutron stars?

Rapidly rotating, magnetised and accreting neutron stars may not be axisymmetric. Gravitational waves can provide one of our few ways to determine the interior structure and motions[2].

Source	GW data	GW+EM data
radio and X-ray pulsars, low-mass X-ray binaries (LIGO)	spin, interior structures, neutron star mountains and mass multipole moments induced by interior magnetic fields or accretion	accretion rate, spin up/down, exterior magnetic field, detection of core-crust differential rotation, thermal properties

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